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ORIGINAL PAPER

Tri-generation power plant and conventional boilers: pollutant flow rate and atmospheric impact of stack emissions

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Abstract The atmospheric impact of stack emissions from a power plant (tri-generator and boilers) that will be installed in an urban area in the central Po valley (Northern Italy), characterized by calm wind events, is studied and compared with the impact of the existing plant (conventional boilers). Both the plants are supplied by methane gas. The atmospheric dispersion of NO_x emitted is simulated, both in the current and future scenario, by the software package ARIA INDUSTRY. The NO_x emission rates are set equal to the regulatory emission limits for existing and future boilers, while the tri-generation system emission rates are set equal to the emission limits certified by the system manufacturer. The simulation periods focus over the 2010 winter season. The simulation estimates the impact of NO_x emissions on air quality (vertical concentration profiles and concentration maps at the ground) in the urban area close to the plant. The future power plant impact on air quality results lower than the impact of the existing plant, even if the yearly total mass of pollutants emitted in atmosphere from the new power plant is higher than from the existing plant. The emissions of conventional boilers result the main responsible of the air pollution at the ground in the future scenario.

Keywords Atmospheric pollution · Dispersion model · Methane-fuelled boiler emission · SPRAY · Tri-generation power plant emission · Vertical concentration profile

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Introduction

The reduction in energy consumption and the increase in energy efficiency, the increase in energy production from renewable sources and the reduction in greenhouse gas (GHG) emissions, are firm commitments set by the European Commission to meet the ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC) to prevent dangerous anthropogenic interference with the climate system.

In order to contribute to the achievement of this long-term goal, the European Commission (E.U. 2009) set out the three targets of 20 % increase in energy efficiency, 20 % increase in use of renewable energies, at least 20 % reduction in GHG below 1990 levels, by 2020. During the drafting of the Directive 2009/29/EC, the European Commission conceived a number of preparatory protocols and actions, including the promotion of the "cogeneration" (E.U. 2004). Combined heat and power (CHP), or cogeneration, implies that heat and electricity are produced simultaneously in one process, combining electricity production technologies with heat recovery equipments (Dharmadhikari 1997). The use of CHP helps to reduce the environmental impact of power generation, because the CHP self-production of electric power reduces the needs of electricity generation from conventional systems. For these reasons, a higher penetration of cogeneration plants has received policy support. The share of electricity produced from CHP in the EU-27 is in growth since 2008 (European Environmental Agency 2012a).

A tri-generation power plant combines the production of electricity and heat to an energy absorber, in order to provide also a cooling system for buildings, and allows primary energy saving and reduction in energy supply costs compared to a traditional system. Moreover, tri-generation plants are often also located close to the end-consumer of heat and electricity, limiting transmission and distribution losses.

The self-production of electric power by a tri-generation plant reduces the needs of electricity supply from the national Electric Energy Network (EEN) respect to a traditional power plant, and therefore, the pollutant (mainly NO_x, SO_x and PM_{10}) and GHG emissions due to conventional electricity generation are avoided.

The effect of the reduction in NO_x, SO_x and PM_{10} emissions improves the air quality in the surroundings of the electric energy production plant (Levy and Spengler 2002), that in most cases is very far away from the sites of end use of the electricity.

The effects of the reduction in greenhouse gas emission (CO_2) have a relevance on a global scale (Houghton et al. 2001). The European Environmental Agency has estimated (European Environmental Agency 2012b) that doubling the share of cogeneration in gross electricity production for EU-27 from 1994 to 2010 could lead to avoided CO_2 emissions for more than 65 Mt CO_2/year by 2010. Therefore, cogeneration is classed as a low carbon technology.

As mentioned above, there is growing interest in using CHP to meet both national and also local targets for reducing GHG and pollutant emissions in atmosphere. Therefore, the potential benefit on local air quality by switching from a traditional power plant to a tri-generation plant must be evaluated by the comparison of their stack emissions rates. The local atmospheric impact of a combustion plant depends upon its emission performance and on the dispersion of its stack emissions in atmosphere: the possible accumulation of the emitted pollutant at ground level in the surroundings of the plant must be assessed under the most critical condition, and the ground-level concentration of emitted pollutants compared with air quality regulatory limits.

In the case study presented in this work, a new power plant consisting of a tri-generation unit with one four-stroke engine and five auxiliary devices (three conventional boilers and two industrial steam generators) will be installed in the general hospital of a Northern Italy town (Modena, central Po valley, 34 m a.s.l.), to replace an existing, dated, plant with three boilers and two industrial steam generators. Both plants are supplied by methane gas. The self-production of electric power from tri-generation unit is expected to almost fulfil the electric energy requirements of the general hospital, cooling of buildings included.

The comparison of the total amount of pollutant yearly emitted in the atmosphere from the new and the existing plant is not sufficient to assess the severity of their impact on air quality, because the exhaust gas emission rate from their stacks varies significantly depending on fuel consumption, i.e., on the operational procedures. The new plant follows a different operating procedure compared with the existing one: the tri-generation unit operates almost steadily, while two of the five auxiliary devices operate only during periods of higher energy demand and during the tri-generation unit maintenance stops. The remaining three auxiliary devices, installed to meet safety and prevention criteria, are generally inactive. The daily fuel consumption of the new plant is fairly steady during the year (tri-generation unit maintenance stops a part). On the contrary, the fuel consumption for the existing plant shows a wide seasonality, with a peak in winter.

Therefore, the scenarios of present and future power generation plant of the general hospital of Modena (Northern Italy) are studied by the simulation of the dispersion in atmosphere of the pollutant plume emitted from the stacks of the existing plant and of the new plant, respectively, involving year 2010 as a test period. Simulation period was divided into winter and summer, although main analysis focussed on winter in order to investigate the most critical meteorological conditions in the Po valley (Ferrero et al. 2011) and the highest fuel consumption period. The simulation focussed on NO_x dispersion, being the most critical pollutant for methane-fuelled plants. Winter was taken as January to March 20th, Summer as June to August 31st. The simulation is performed by the software package ARIA INDUSTRY (Arianet s.r.l., Milano, Italy) (Tinarelli et al. 1998, Tinarelli et al. 2000).

Materials and methods

The new plant: tri-generation unit and boilers

The new power plant will be installed at the general hospital, within the city of Modena, in a densely populated urban area. The tri-generation unit will be a Jenbacher JMS 620 GS-N. L (electrical power 3,349 kWe, thermal power 3,098 kW_t, electric efficiency 44.2 %, thermal efficiency 40.9 %) with an internal combustion four-stroke engine powered by methane gas. A typical efficiency value (European Environmental Agency 2012a) for co-generator unit is approximately 75–90 % for the combined heat and electricity generation.

The tri-generation unit will be supported, when requested, by auxiliary devices (three conventional boilers and two industrial steam generators will be installed). The features of the new plant are reported in Table 1.

The regulatory limits for atmospheric emissions of an internal combustion four-stroke engine are set by Italian law (D. L. 152/06). The tri-generation plant manufacturer certifies emission rates lower than the regulatory limits, and

Table 1 The new plant components at the nominal conditions (100 % loading rate)

Device	Nominal power (kW_t)	Thermal power (kW_t)	Emitted dry gas flow (Nm^3/h)	Emitted gas temperature (°C)	O_2 (%)	Stack height (m)	Stack diameter (m)	Service
Boiler 1	5,200	5,653	5,221	170	3	10	0.7	Hot water production
Boiler 2	5,200	5,653	5,221	170	3	10	0.7	
Boiler 3	2,800	3,027	2,811	170	3	10	0.7	
Steam generator 1	2,081	2,312	1,937	215	3	10	0.5	Steam production
Steam generator 2	2,081	2,312	1,937	215	3	10	0.5	
Tri-generation unit		3,098	13,920	125	11.2	15	0.7	Hot water recovery

equal to: NO_x (as NO_2) <250 mg/Nm^3, CO <300 mg/Nm^3, PM_{10} <30 mg/Nm^3, evaluated in the exhaust dry gas flow with 5 % oxygen (O_2) and specific emission of $CO_2 = 510$ g/kWhe.

The designer has defined a yearly plan of operation for the new plant, able to cope with the peak power demand. The activity of the new plant devices is modulated on the hourly energy needs of the general hospital: for each month of the year, a "typical" day of operation at hourly time step has been planned. The tri-generation unit will operate 7,010 h/year (3,471 from October to March and 3,539 from April to September) at the nominal conditions, while two of the other devices, one boiler and one steam generator, will operate, upon request, at a loading rate <50 %. The regulatory limits for emissions of methane supplied boiler with a nominal power lower than 50 MW are set by Italian law in the exhaust dry gas flow with 3 % oxygen (O_2): NO_x (as NO_2) = 350 mg/Nm^3, SO_x = 35 mg/Nm^3, PM_{10} = 5 mg/Nm^3, CO = 100 mg/Nm^3 (D. L. 152/06 and local administration for CO limits).

Even if the tri-generator electric power production is expected to fulfil the needs of the general hospital, it has been prudently estimated that up to 4,013 MWhe/year of electric energy should still be supplied by the Italian EEN.

The existing plant

The current central heating of the general hospital provides power for heating, hot water and other services (industrial steam production). It includes five generators (three conventional boilers and two steam generators) supplied by methane gas, with a total nominal power of 19,767 kW. The regulatory limits for emissions of methane supplied boiler with a nominal power lower than 50 MW set by Italian law have been previously reported (D. L. 152/06 and local administration for CO limits). The plant was sized with security criteria: only three of the five generators operate continuously. The main features of the existing plant are reported in Table 2.

The dry exhausts flow rate from the existing plant have been calculated from the fuel consumption for year 2010, since no emission monitoring data were available. Emissions flow rate for the three devices currently operating (E0, E1, E4) have been estimated assuming mass conservation and steady-state operation for all of them. The 2010 record of daily fuel consumption shows a very high variability, ranging from 22,143 Sm^3/day (peak consumption in winter) to 2,067 Sm^3/day (minimum consumption in summer). Consequently, a high variability results in the daily exhaust gas emission rate from the current plant stacks and, finally, in the daily mass of pollutants emitted into the atmosphere. The average exhaust gas temperature, currently monitored for the three active devices, is 150 °C with 2.9 % oxygen (O_2).

Presently, the cumulative yearly supply of electric energy for the general hospital, the central heating unit and buildings' cooling is of 25,494 MWhe/year and is provided by the Italian EEN.

Table 2 The existing plant components at the nominal conditions (100 % loading rate)

Device	Nominal power (kW_t)	Thermal power (kW_t)	Emitted gas temperature (°C)	Stack height (m)	Stack diameter (m)	Service
Boiler E0	4,652	5,168	180	11.3	0.75	Hot water production
Boiler E1	4,651	5,227	180	11.3	0.75	
Boiler E2	4,651	5,227	180	11.3	0.75	
Steam generator E3	2,325	2,558	160	11.3	0.70	Steam production
Steam generator E4	3,488	3,830	160	11.3	0.70	

Annual mass flux of pollutants emitted in atmosphere by the new and the current plant

A previous study showed (Ghermandi et al. 2011) that the total amount of NO_x, CO, PM_{10} and CO_2 yearly emitted in the atmosphere by the tri-generation unit alone results higher than the total yearly emission from the existing plant (test year 2010). The annual pollutant mass flow in the future scenario would result even higher if also the emissions from the two auxiliary devices (boiler and steam generator) were counted.

The annual mass fluxes evaluated for the new and the existing plant are reported in Table 3. Emissions due to electric energy production supplied by Italian EEN were estimated from the atmospheric emission inventory for electric energy production plants in Italy (ENEL 2010), assuming the yearly needs for the general hospital in the future (4,013 MWhe/year) and current (25,494 MWhe/year) scenario mentioned above.

The comparison between the total yearly emissions in the two scenarios, including both the mass fluxes from plant stacks and also the emissions due to electric energy production from Italian EEN, shows that the total amount of NO_x, CO, PM10 yearly emitted results higher in the future scenario. On the contrary, the annual CO_2 flux results higher in the current scenario, because of the great amount of CO_2 yearly emitted to produce electricity by Italian EEN: furthermore, the annual CO_2 flux in the future scenario will likely be lower than reported in Table 3, because the tri-generator electric power production is expected to fulfil the needs of the general hospital, as mentioned above, and the CO_2 emissions corresponding to the prudently estimated electric energy supply in the future scenario (1693 times/year) will be averted. The relevant reduction in emissions from electric energy production switching from the existing to the new plant (avoided emissions) does not improve the air quality in the surroundings of the tri-generation plant, but close to the electric energy production plant, as above mentioned. A great amount of NO_x, SO_x and PM10 emissions due to electricity production by Italian EEN is also averted replacing the existing with the new plant, but an overall meaningful budget could only be done for CO_2, because greenhouse gas emission reduction has relevance on global scale (Meunier 2002).

The difference in stack emissions between the new and the current plant is a key factor in assessing the new plant impact on local air quality. Estimating this impact by simply comparing the yearly pollutant emission of the two plants would show an adverse impact of the new plant for all emitted pollutants but SO_x. However, also the operating mode of the new and existing plants needs to be taken into account for a correct impact assessment, and the local impact on air quality has to be evaluated. The simulation of the atmospheric dispersion of the pollutant plume emitted from the stacks of the future and of the current plant, performed both for winter and summer 2010, has been therefore focused on the most critical operating condition for both plants and under meteorological situations unfavourable to pollutant dispersion (Ferrero et al. 2011), i.e. on winter season. For this reason, this study mainly presents and discusses the simulation results over winter period.

Table 3 Annual mass emission of pollutants from the new and the existing plant and annual mass emissions due to the production of electric energy supplied by the Italian EEN

Pollutant	Fluxes in atmosphere from plant stacks (t/y)			Emissions due to electric energy production by Italian EEN (t/y)	
	Future scenario		Actual scenario	Future scenario	Actual scenario
	Tri - generator	Auxiliary devices	Existing plant		
NO_X	14.94	4.57	10.62	0.95	6.04
CO	17.93	1.31	3.03		
SO_X		0.46	1.06	0.91	5.81
PM_{10}	1.79	0.07	0.15	0.05	0.31
CO_2	11,347	2,522	5,865	1,693	10,758

Modelling of the plume dispersion in atmosphere

The simulation is performed by the software package ARIA INDUSTRY that includes: the dispersion model SPRAY, the diagnostic meteorological model MINERVE (Geai 1987; Desiato et al. 1998; Finardi et al. 1998; Cox et al. 1998; Cox et al. 2005) and the turbulence model SURFPRO. SPRAY (Tinarelli et al. 1998; Tinarelli et al. 2000) is a Lagrangian stochastic model for the simulation of the dispersion of passive pollutants in complex terrain under non-homogenous conditions. The model operates in non-stationary conditions by approximating temporal variations in successive stationary states. SPRAY is based on a three-dimensional form of the Langevin equation for the random velocity (Thomson, 1987; Rodean, 1995). The turbulent velocity u' and the displacement dx of each particle are given by the following equations:

$$du'_j = a_i(x,\ u)dt + b_{ij}(x,\ u)dW_j(t) \quad (1)$$

$$dx_j = (U_j + u'_j)dt \quad (2)$$

where $i, j = 1, 2, 3$, x is the displacement vector (*i.e.* vector of particle position), U_j is the mean wind velocity vector, u is the Lagrangian velocity vector, $a_i(x,\ u)dt$ is a deterministic term, $b_{ij}(x, u)dW_i(t)$ is a stochastic term and the quantity $dW_i(t)$ is the incremental Wiener process with average 0 and variance dt. The deterministic coefficient depends on the probability density function (PDF) of the turbulent velocity and is determined from the Fokker–Planck equation. In two horizontal directions, the PDF is assumed to be non-homogeneous Gaussian. In the vertical direction, the PDF is assumed to be non-Gaussian to describe non-uniform turbulent conditions. In this case, the Gram–Charlier series expansion is adopted (Anfossi et al. 1997; Ferrero and Anfossi 1998). The diffusion coefficient $b_{ij}(x, u)$ is obtained from the Lagrangian structure function and is related to the Kolmogorov's universal constant, C_0 (Du 1997), and to the dissipation rate of turbulent kinetic energy ε, as the following equation:

$$b_{ij} = \sqrt{C_0 \varepsilon} \tag{3}$$

$b_{ij}(x, u)$ can be also determined from the variances of the velocity fluctuation and the Lagrangian decor relation time scale T_{Lij}, namely:

$$b_{ij} = \sqrt{2\sigma_{ij}^2 / T_{L_{ij}}} \tag{4}$$

Since

$$T_{L_{ij}} = 2\sigma_{ij}^2 / C_0 \varepsilon \tag{5}$$

The SPRAY model is able to simulate atmospheric dispersion and deposition-decay phenomena also over complex topography (e.g. Gariazzo et al. 2004); it gives a highly reliable simulation of pollutant dispersion close to the source also in low-wind conditions (Ghermandi et al. 2012). SPRAY supplies a 3D concentration field subdivided into grid cells vertically structured into terrain-following layers, and the grid is vertically stretched to obtain higher resolution near the ground. The thickness of the first layer is 10 m, starting from the ground.

The studied area is centred at the emission source, i.e., the location of the current and future power plant, close to the general hospital of Modena. The spatial domain for diagnostic wind field estimation covers an area of 40 × 40 km, divided into a horizontal grid of 500 m square cells and into a vertical grid of 30 layers from the ground to 1,800 m. For the computation of pollutants concentration fields, the domain is limited to an area of 20 × 20 km, centred at the emission source and divided into a grid of 250 m square cells. The emission sources are simulated as continuous point sources. The simulations are performed using both simulated and measured meteorological data for the year 2010. Meteorological observations have been acquired at the ground stations of the Osservatorio Geofisico of the University of Modena and Reggio Emilia (Modena, Italy) and of the Regional Environmental Agency (ARPA). Meteorological simulated data comprise of mesoscale vertical wind profiles and mixing height: these data have been provided by ARPA using CALMET model (Deserti et al. 2001), which requires input meteorological ground measurements and radio sounding profiles of temperature and wind speed [CALMET is often used to generate meteorological field also for air quality models, even coupled with larger-scale models (Yim et al. 2007; Cox et al. 2005; Chandrasekar et al. 2003; Jackson et al. 2006)]. Ground elevation data have been provided by Shuttle Radar Topography Mission through United States Geological Service (USGS), sampled at 3 arc-seconds, while land use–land surface cover dataset is extracted from the European CORINE Land Cover 2000 dataset (European Environment Agency) in raster format with a spatial resolution of 100 × 100 m.

Part of the present paper is included in the Environmental Impact Analysis presented to Administrative Authorities. Previous studies showed the successful use of SPRAY as a regulatory model (e.g. Ferrero et al. 2001; Ghermandi et al. 2012), thanks to its ability to provide a correct estimate of ground-level concentrations both in complex circulation patterns (e.g. Gariazzo et al. 2007) and in low-wind or calm conditions, as mentioned above. The SPRAY model has been used in studies dealing with urban air quality (Breznik et al. 2003; Calori et al. 2006) and has been applied to simulate mesoscale dispersion, chained with other models (Armand et al. 2004).

Results and discussion

Comparison between current and future plant

The atmospheric dispersion of the emission plume has been simulated on an hourly basis under most critical operating conditions, i.e., during winter, for both plants and both scenarios. Simulation time step has been set to 1 h, due to the hourly meteorological input data. The 2010 winter season was characterized by meteorological conditions adverse to pollutant dispersion, due to a frequency of low-wind events (i.e. wind speed <2 m/s) equal to 74 %. Moreover, maximum hourly mixing height in winter 2010 ranged between 250 and 600 m, reaching 800 m in late February, consistently with typical mixing height observation within the Po valley (Ferrero et al. 2011; Pernigotti et al. 2012). These meteorological conditions, favourable to pollutant accumulation in the atmosphere, characterized the central part of the Po valley in autumn and winter 2010 and have been enhanced by the flat topography of the area. Simulations focussed on NO_x, being the most critical pollutant for methane-fuelled plant. Moreover, NO_x

concentration in urban areas, in case of intense vehicular traffic emissions, may be close or higher than regulatory limit. Besides, in the urban area of Modena, NO_x hourly average concentration results one of the most critical pollutant among those emitted by the investigated plant stacks (Bigi et al. 2012).

In order to represent the worst-case scenario, the current plant is assumed to operate continuously at the maximum daily fuel consumption for year 2010 (i.e. 22,143 Sm^3/day, occurred in winter 2010) and corresponding to the highest emission flow. This fuel consumption results in a cumulative dry exhaust flow rate from all three operating devices of the current plant stacks of $\sim$10,000 Nm^3/h, with average exit velocity of gas emissions of 3.2 m/s. However, this fuel consumption value is not uncommonly high in winter: the average daily fuel consumption for winter 2010 is 16,194 Sm^3/day (st. dev. 13 %), while the 90th percentile is 19,275 Sm^3/day. The NO_x emission flow rate into the atmosphere has been evaluated assuming always the pollutant concentration in the emissions equal to the regulatory limits. Beyond the critical conditions stressed in the simulation, the impact on air quality in the actual scenario is determined by the combined effect of the emission rate trend and of the concurrent meteorological conditions.

The tri-generation unit and the two auxiliary devices (one boiler and one steam generator) of the new plant are assumed to operate according to the designed operation plan. In winter season, the tri-generation unit is expected to operate almost constantly at 100 % loading rate for all hours of the day, while the two auxiliary devices operate several hours a day at loading rate <50 %. It implies that the flow rate from the tri-generation unit stack will be fairly constant throughout the winter; the NO_x emission into the atmosphere has been evaluated assuming the pollutant concentrations in the emissions certified by the plant manufacturer for the tri-generation unit and equal to the regulatory limits for the two auxiliary devices. Given the quite steady tri-generation unit activity, the strength of its impact on air quality will be mainly driven by the occurring meteorological conditions. On the contrary, the auxiliary devices impact will be significantly affected by their emission rate trend.

In this study, both the current and future plant are assumed to bear the same peak heat demand, i.e., both plants are assumed to operate under most critical conditions.

Figure 1 shows the maps of average hourly NO_x ground concentration (i.e. in the first atmospheric layer, 10 m deep) from the plume emitted by the power plant of the main hospital of Modena in the current and future scenario. The simulation period ranges from January 1st to March 20th 2010. The plant stack location (that is the same both in the current and in the future scenario) is the centre point of the domain. Each single stack is simulated as an independently emitting source.

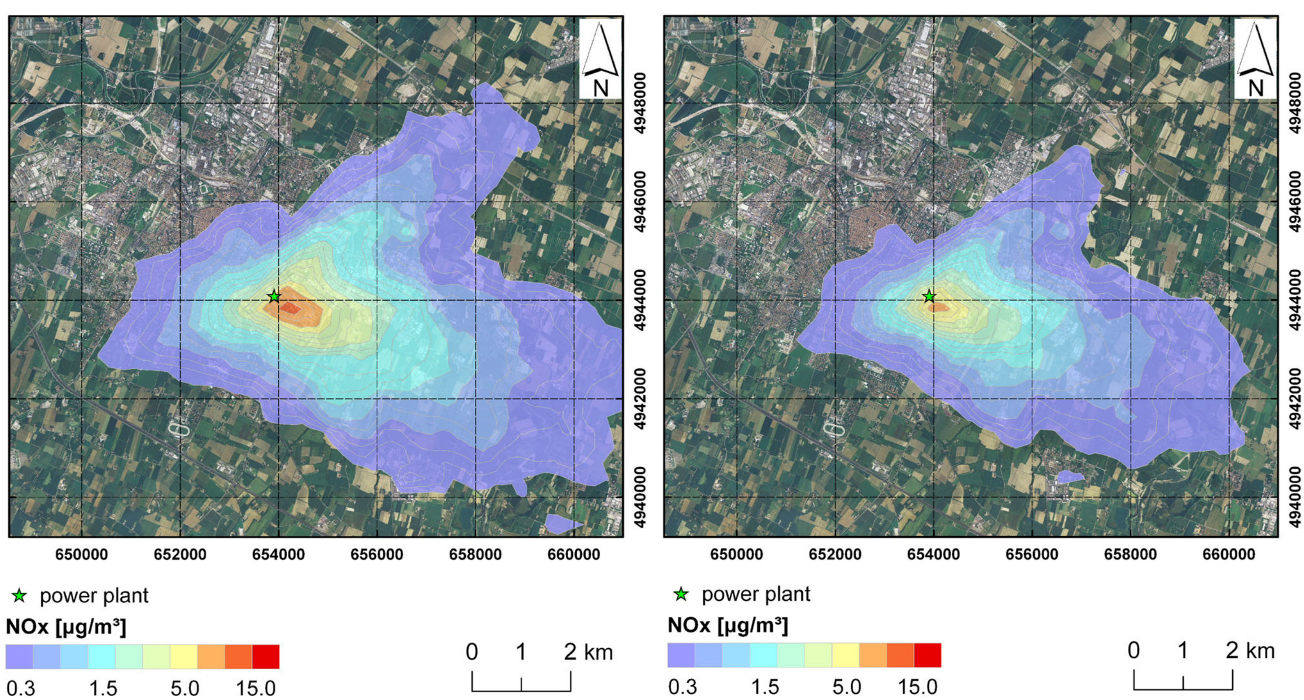

Fig. 1 Average hourly NO_x ground concentration plumes from the current plant of the main hospital of Modena (*left*), and from the new plant (*right*), simulated by SPRAY for the 2010 winter period. The *star* indicates the location of plant stacks. The *colour scale* refers to NO_x concentration

The simulated plumes, both in the current and the future scenario (respectively panel left and right in Fig. 1), are stretched along the main wind direction (approximately from North–West to South–East), although the surface representing the area with minimum ground-level concentration is larger in the current than in the future scenario. Air quality limits for NO_2 (maximum hourly concentration 200 $\mu g/m^3$, E. U. 2008) have been compared to the simulated NO_x (as NO_2) shown in the maps (Fig. 1): in the current scenario, the average NO_x concentration in winter ranges from 0.3 to about 15 $\mu g/m^3$, while in the future scenario, the highest concentration values are equal to 7 $\mu g/m^3$. In case of a more conservative simulation of the current plant assuming the average daily fuel consumption for winter 2010 instead of its maximum, the resulting atmospheric NO_x concentrations would result $\sim$27 % lower, but still higher than the simulated results of new plant. The impact of the current plant to near-ground atmosphere results the largest also because the exit velocity of gas emissions from the tri-generator is much higher than that from conventional boilers, as explained below.

The average of maximum NO_x hourly concentrations from all winter simulations resulted in 69 and 21 $\mu g/m^3$ for the existing and new plant, respectively. The average value of concentration maxima for the current plant reaches the 34.5 % of the regulatory limits (200 $\mu g/m^3$), while for the new plant represents about the 10 % of the regulatory limits.

These results indicate that, in winter, atmospheric NO_x concentration in Modena may be significantly affected by the current plant emissions, eventually leading to concentration values closer to the air quality limits in case of weather conditions favourable to pollutant accumulation. The NO_2 average atmospheric concentrations measured, for year 2010, by local environmental agency (ARPA) in a urban site in Modena at about 3 km from the plant location (Table 4) are characterized by the heavy vehicular traffic and clearly show the potential impact of current plant emissions on local air quality.

In seasons other than winter, the fuel consumption from the current plant is lower, leading to lower emissions. The impact of stack emissions is minimum in summer due to the annual maximum in atmospheric mixing enhancing pollutant dispersion and the minimum in fuel consumption: the average daily fuel consumption for summer 2010 is $\sim$17.4 % of 2010 average winter value, leading to an analogous reduction in the NO_x emission rate. A comparison of simulation results for each season shows NO_x concentration at ground decreasing from winter to summer down to 1 $\mu g/m^3$ or lower.

Table 4 NO_2 seasonal average atmospheric concentrations in a urban site in Modena (local ARPA)

Pollutant	Winter ($\mu g/Nm^3$)	Spring ($\mu g/Nm^3$)	Summer ($\mu g/Nm^3$)	Autumn ($\mu g/Nm^3$)
NO_2	80.51	50.84	42.54	57.48

Given the quite steady tri-generation unit activity, also its emission flow is expected to be quite steady throughout the year; on the contrary, the planned auxiliary device activity is variable throughout the year, with inactivity (the boiler) or very low loading rate activity (the steam generator) in summer, leading to a minimum impact on air quality in summer also for the new plant.

New plant emissions: the individual contribution of the devices

To determine the contribution of each emission source of the new plant, a simulation was performed by considering either the tri-generator, or the boiler along with the steam generator, each one operating at the design conditions. The simulation period ranges from January 1st to March 20th 2010, and the same reference and meteorological data used for the previous simulations are assumed. Figure 2 represents the maps of simulated average hourly NO_x ground concentration.

The plumes resulting from the simulation of the tri-generation unit and of the combined boiler and steam generator emissions (respectively panel left and right in Fig. 2) clearly show the different individual contribution to the average hourly ground concentration field. Average NO_x concentrations from tri-generator peaks at 1.4 $\mu g/m^3$ (concentration value occurring at about 400 m from the source), while for boiler and steam generator plume, the highest NO_x concentration values are equal to 5.6 $\mu g/m^3$ (concentration value occurring at about 220 m from the source). The maximum hourly average concentration values in the maps of the individual sources may fall in different points respect to the maximum for the total plant (Fig. 1 right), because each source has its own concentration field. The average of maximum NO_x hourly ground concentrations from tri-generator emissions resulted in 9.3 and 16.1 $\mu g/m^3$ for boiler and steam generator emission plume.

The NO_x emission rate from tri-generation unit is considerably higher than from boiler and steam generator: the ratio between tri-generator and either the boiler or the steam generator NO_x emission rates ranges between 3.2 and 10 over the simulation period, depending on the occurring operational conditions of each unit. In addition, the emissions from conventional boilers have higher temperature than tri-generator exhausts, which are cooled by the heat recovery (Table 1). Nevertheless, the impact by conventional devices to near-ground atmosphere results the largest, because the exit velocity of gas emissions from the

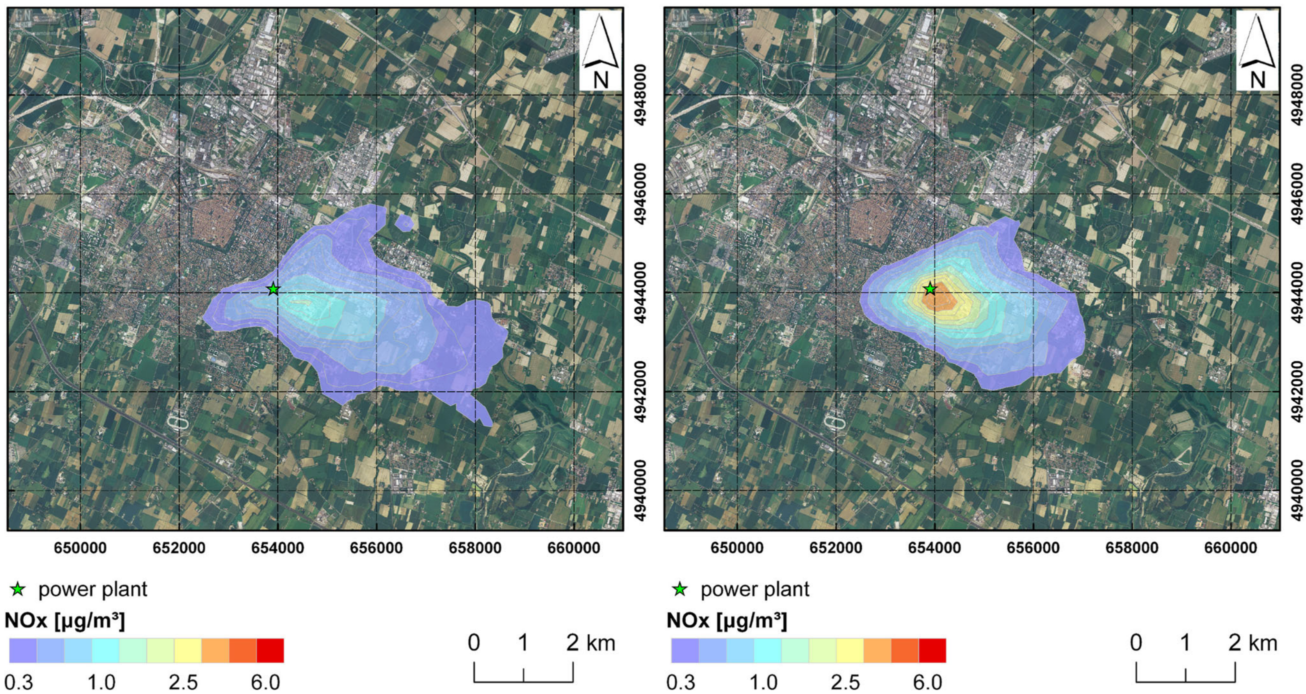

Fig. 2 Average hourly NO_x ground concentration plumes from the individual sources of the new plant of the main hospital of Modena, the tri-generation unit (*left*) and the boiler and steam generator (*right*), simulated by SPRAY for the 2010 winter period. The *star* indicates the location of plant stacks. The *colour scale* refers to NO_x concentration

tri-generator is ten times higher than that from boiler and steam generator. The average exit velocities used in the simulation are 15.10 and 1.56 m/s for the tri-generator and the conventional boilers, respectively. In addition, the stack height of boiler and steam generator is lower than the tri-generator one (Table 1). The dynamic plume rise is calculated by SPRAY as reported in Anfossi et al. (1993), with a conservative approach, and possible rise enhancement effects due to merged plumes respect to single emissions (Anfossi et al. 1978; Anfossi 1985) are not considered. The combined effect of exit velocity of exhausts and stack height is well shown by the vertical NO_x concentration profiles in the atmosphere. These profiles result from the concentration values in the cells of an air column starting at the ground and passing through all the atmospheric layers in which SPRAY structures the 3D domain. The vertical NO_x profiles obtained for the total emissions of the new plant (tri-generator, boiler and steam generator) and for the individual emission plumes of the tri-generator, the boiler and the steam generator are shown in Fig. 3 (panel left). These vertical profiles are taken at the peak for NO_x hourly average ground concentration by total emissions of the new plant (P1, Fig. 3, right; 654 106 E, 4 943,881 N, UTM32-WGS84), value occurring 270 m south-east of it. The vertical NO_x profiles show clearly that the boiler and steam generator emissions control the high concentration values at ground level, while their impact decreases rapidly with height. On the contrary, the tri-generation unit emissions cause a significant NO_x concentration peak at almost 70 m above the ground, where total NO_x concentration is about 11 µg/m^3 and higher than at the ground.

In Fig. 3 (panel right), the trend of the vertical NO_x concentration profile (total new plant emissions) has been investigated along the main wind direction (approximately from North–West to South–East) at the position P1, i.e., at the peak for ground concentration. The concentration profiles were truncated at 140 m HAGL (height above ground level). The profiles result gradually smoothed with the increasing distance from the source: the concentration peak at about 70 m altitude is significantly smoothed at about 2 km from P1. This behaviour is particularly evident in low-wind conditions, when the vertical dispersion of pollutants due to the atmospheric turbulence is widely prevailing over transport along wind direction. To profile smoothing at increasing distance from sources might also contribute the attainment of the good mixing that can happen at different distance depending on the atmospheric conditions (Slawson and Csanady 1971).

The trends of vertical concentration profile along other directions are quite similar one each other and do not differ strongly from the trend along the main wind direction reported in Fig. 3 (panel right), because of the moderate

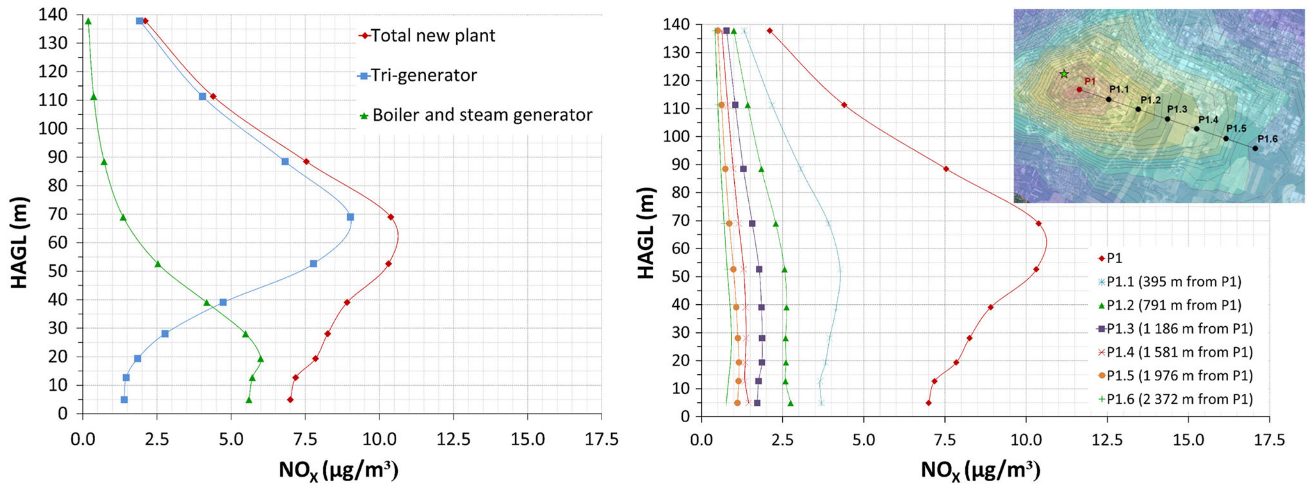

Fig. 3 *Vertical* profiles of average hourly winter NO_x concentration both from the total emissions of the new plant and from its individual sources separately (*left*). *Vertical* profiles for average hourly winter NO_x concentration for the new plant total emissions along the main wind direction (*right*)

wind speed intensities and the very high frequency of low-wind events occurring in winter 2010.

New plant emissions: daily NO_x concentration patterns

The daily NO_x concentration patterns at different heights above ground are also obtained from the 3D simulation performed by SPRAY for winter 2010 (from January 1st to March 20th 2010).

The hourly NO_x concentrations from the new plant emissions at the midpoints of the first ten atmospheric layers above ground level in which SPRAY structures the 3D domain are reported in Fig. 4, together with the corresponding mixing layer (ML) depth. Hourly NO_x concentrations from the total new plant emissions and, separately, from the individual sources of the plant (i.e. boiler and steam generator and tri-generator) are shown in panel left, middle and right, respectively, of Fig. 4. The hourly mixing height and concentration data are average values for the simulation period.

The daily NO_x patterns at different height along the air column, up to about 100 m above ground level, are clearly affected by the mixing height behaviour (Stull 1988): the daily minimum in NO_x occurs at maximum mixing layer depth. The NO_x concentration peak determined by tri-generator emissions remains confined above the height of 45 m throughout the day.

The daily patterns for the emissions of the individual sources, boiler and the steam generator (Fig. 4, middle panel) and tri-generator (Fig. 4, panel right) confirm that along the air column, throughout the day, the boiler and steam generator emissions control the high concentration values at the ground, while the tri-generation unit emissions have low impact at the ground (concentration values <3 $\mu g/m^3$ up to 20 m above ground).

Figure 5 represents daily NO_x concentration patterns for the new plant total emissions at ten different heights above ground (corresponding to the midpoints of the first ten atmospheric layers in which SPRAY structures the 3D domain, up to 165 m), obtained from simulation spanning over January, February and March 2010 separately. Figure 5 shows that the atmospheric stability, which favours concentration peak development at height above the ground in January and February during night time, results largely missing in March, when the mixing phenomena gradually start to dominate the planetary boundary layer dynamics, with mixing layer depth up to about 1,400 m, and the hourly concentration values are significantly lower throughout the air column.

The confinement of the tri-generator emissions at height far above the ground level is consistent with an application of SPRAY to the dispersion of the plume emitted by high power plants presented by Trini Castelli et al. (2002, 2003): the authors of these studies investigated a cogeneration plant of 180 MW installed to supply central heating to a town district replacing small domestic boilers. This plant, equipped with a 50 m high stack, showed a NO_x emission rate at least ten times higher than that of the tri-generation system here described; however, similarly to the result of the present study, the new power plant led to an improvement in local air quality, also at ground level. This outcome originates from the different dynamics of the emission plumes between the two source type, relying on their different emission height, exit velocity and buoyancy fluxes. Each plume experiences different wind and turbulence conditions, determining their respective 3D

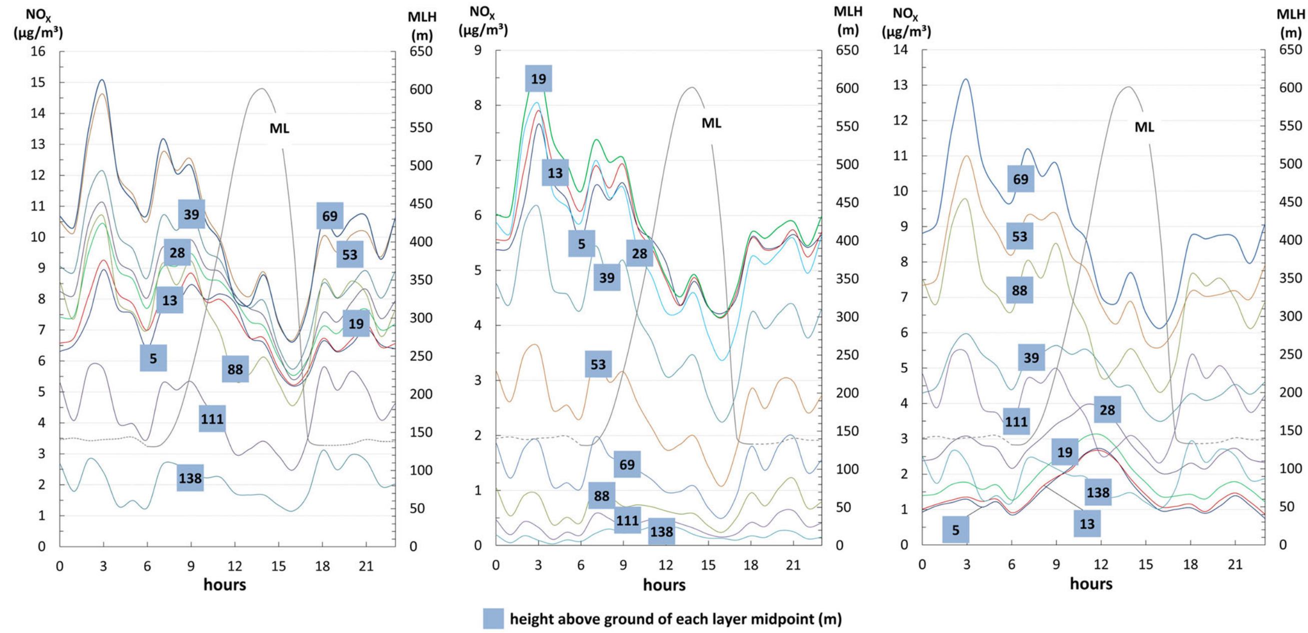

Fig. 4 Average hourly NO_x concentrations from total new plant (*left*), boiler and steam generator (*middle*) and tri-generator (*right*) emissions, at ten different heights above ground level. Average hourly mixing height (MLH) in winter 2010 is also represented

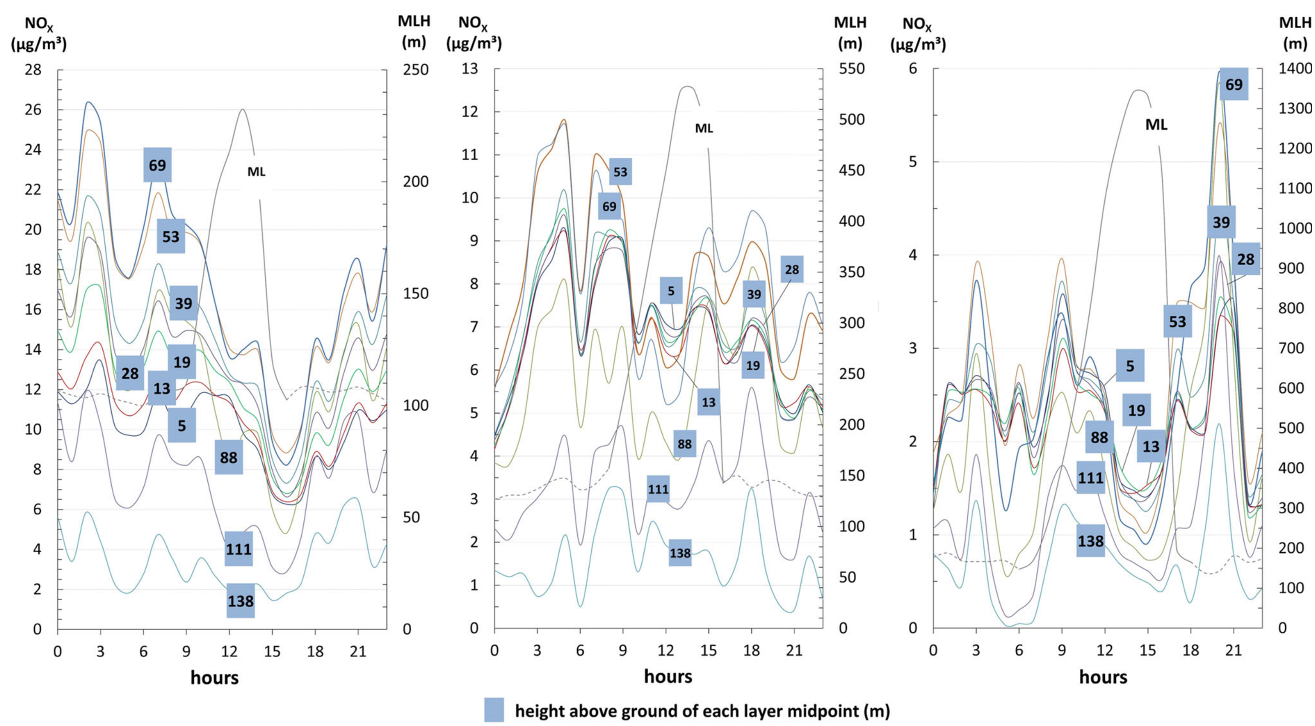

Fig. 5 Average hourly NO_x concentration from the total new plant emissions at ten different height above ground level, with the hourly mixing height (MLH) for January (*left*), February (*middle*) and March (*right*) 2010

distribution in atmosphere, but all of them are highly realistically simulated by the Lagrangian stochastic model SPRAY in the 3D domain. The plume rise evaluation in the present study is calculated with a conservative approach, as previously mentioned, without accounting for the merging of different plumes.

The contributions of the emitted plumes, simulated by SPRAY throughout the spatial domain, provide 3D concentration fields and ground-level concentration maps that are suitable for regulatory purpose.

Conclusion

A new power plant including tri-generator and auxiliary conventional generators will be installed in the urban area of Modena (central Po valley, Italy), to supply the city hospital. Comparison of atmospheric impact of stack emissions from the existing conventional boilers and future plant has been performed. Annual stack emissions in the atmosphere, evaluated as total mass flux of pollutants, result higher for the new plant than for the current plant, although this is not unusual when switching from a methane-fuelled plant to another, since for these kind of plants, the emissions are quite modest and the margins of improvement may be small (Pehnt 2008).

However, the impact on local air quality of a plant depends on the atmospheric dispersion of the emitted plume that is affected by the stack plant height and design and by the emitted gas flow, and strongly depends on the occurring meteorological conditions, besides the height and the design of the stack and the emissions flow. A simulation of NO_x dispersion from the stack of the plant, both in the current and future scenario, performed by SPRAY model using winter 2010 as test period, proved the influence of the different operating mode of the existing and new plants in impacting local air quality. The current plant emissions have a strong seasonality: in winter, they may lead to NO_x local concentration close to the regulatory limits and significantly higher than the concentration due to the new plant emissions. The individual contribution of the different devices of the new plant, i.e., the tri-generation unit, the boiler and the steam generator, has been investigated. The tri-generator emissions will be fairly steady throughout the year, and even if in late spring and summer season result higher than current plant emissions, they do not influence significantly local air quality at the ground. On the contrary, the impact of the emissions from the two auxiliary devices, which will operate only during high energy demand periods, results relevant at the ground, mainly because of the low exit velocity of the exhaust gas from their stacks. The vertical NO_x concentration profiles and NO_x daily patterns at different height above ground level show that the tri-generation unit emissions cause very low NO_x concentration at ground level at all hours of the day also in the most critical winter month of the tested period (January 2010). Finally, the study shows how switching from the existing to the new plant will improve the air quality in the surroundings of the power plant, where its emission plume disperses.

Furthermore, the present study stresses the role of the plume rise in reducing the emitted pollutant impact at ground level, also in meteorological condition favourable to pollutant accumulation in atmosphere: the tri-generation unit contribution to ground concentration is lower because of its higher stack height and higher exhaust gas velocity. This result leads to recommend stack designs increasing the plume rise, notwithstanding the raise in plant costs.

In addition, the case study confirms the effective reduction in GHG emission in atmosphere switching from the existing to the new plant, due to the CHP self-production of electric power.

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